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FOREWORD

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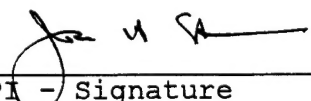
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Introduction

Background

In the course of training, the soldier is exposed to a variety of blast sources (small and large caliber), in a variety of surroundings (in the open and inside enclosures), and for single and multiple rounds. The Surgeon General of the Army must set conditions that limit the exposure of troops to blast overpressure (or "weapon noise") that will result in only a very small incidence of deleterious effects in the soldier population.

Military Standard 1474C (1991) provides rules for determining exposure limits based on auditory hazard. The data used to formulate these limits came from small caliber (high frequency) fire. The Standard assumes that the blast field can be characterized by two parameters: the peak pressure and a time duration. Based on those two quantities, a maximum number of exposures are determined. If the combination of quantities exceeds the "Z-line," the Standard allows no exposures because of unspecified nonauditory danger.

When an exposure exceeds the Standard's nonauditory limits, man-rating studies must be conducted to establish exposure limits on a weapon-by-weapon basis. This is a time-consuming and expensive procedure that is likely to become more and more common as weapon power increases. Furthermore, when the blast overpressure hazard arises in an enclosure, the variation and permutations of the exposure become so enormous that case-by-case studies are not feasible.

When blast overpressure levels increase further, the concern switches from identifying threshold to anticipating soldier performance and effectiveness. Here, the guidance for Army doctrine has come from animal tests, largely concerned with lethality estimates. More recent animal tests and more thorough analysis of previous test data reveals that physiological effects are present at much lower values than had been previously thought and involve all of the body's air-containing organs.

Finally, animal studies that consider the effects of combined trauma have shown that the pathophysiological consequences can be profound, and could have implications both for the individual and for the medical care system. Once again, the elements entering such estimates do not properly reflect what is known about the physiological consequences of blast overpressure, nor is enough known to be able to confidently anticipate the consequences.

Previous Work

Animal Tests. Over the past 15 years, tests have been conducted at the Albuquerque Overpressure Test Site, under the sponsorship of the US Army Medical Research & Materiel Command (MRMC), exposing animals to blast loading. See Richmond, et al (1982), Dodd, et al., (1985), Yelverton, et al., (1993a), and Yelverton, et al., (1993b). Configurations included explosives detonated in the open and in enclosures and simulations of weapons fired from enclosures. The tests were conducted as studies with specific, narrow goals and the results were not systematically organized and analyzed in total.

Much of the experimental design was based on the assumption that respiratory injury had the lowest threshold and that injury to the upper respiratory tract preceded injury to the lung. An analysis of threshold injury levels, however, based on a preliminary compilation of the animal data showed an unexpected prevalence of injury to the gastrointestinal tract (GI) tract and no significant difference in threshold between any of the air-containing organs. See Stuhmiller (1990).

Injury Mechanisms. Since the lung had been identified initially as the most critical major organ injured by blast overpressure, work was conducted to understand the mechanical properties of lung materials, so that models could be constructed. See Fung, et al., (1985). In addition, a theory was advanced connecting tissue damage to the compression wave within the lung. Fung, et al., (1988).

Using the knowledge of the biological material properties, a mechanical model of the thorax wall and lung parenchyma was developed (Yu, 1990). These studies elucidated the reasons why pressure measurements differ between the large airways and the parenchyma. Furthermore, a linear relation was observed between the velocity of the chest wall and the strength of the internal compression wave. This pivotal finding was also confirmed with mathematical simulations (Vander Vorst and Stuhmiller, 1990).

As concern over GI tract injury grew, exploratory work was undertaken to identify the underlying mechanisms. Surrogate models revealed that damage to the tract arises from concentrations of stress at locations near air bubbles (Vasel, et al., 1990). Once the mechanism was understood, the mechanical properties controlling this phenomena could be identified and experiments conducted to determine the values of these properties in small animal intestines (Yu and Vasel, 1990). A surgical procedure was developed for an isolated, perfused model of the rabbit gut in which systematic studies could be conducted (Yu, et al., 1991).

Mathematical Modeling. The first biomechanical models to predict response to blast overpressure were developed by White, et al., (1971). The model was calibrated to

predict the esophageal pressure observed in large animal tests, but attempts to correlate this quantity with lethality were unsuccessful. Later, Josephson et al., revisited the model and concluded that the predicted pressures could not be correlated with injury. Stuhmiller (1986) showed that the empirical correlation of injury with hyperbolic curves on a peak pressure-duration axes are related to the amount of irreversible energy loss in mass-spring-damper systems. These "generic" models formed a theoretical basis from which current biomechanical models, such as Viano and Lau (1988) have been developed.

The first systematic application of this biomechanical approach was made for the tympanic membrane (Stuhmiller, 1989). Finite element modeling was used to transform the geometric details of the membrane and support structures into a mass-spring-damper system. Rupture of the membrane was associated with exceeding the tensile strength of the membrane fibers. The resulting model provided an excellent correlation of observed tympanic membrane rupture in isolated specimens. A summary of the biomechanical modeling approach and its potential for blast overpressure related problems is found in Stuhmiller, et al., (1990).

Hazard Assessment. As mentioned earlier, the military standard for occupational exposure is primarily one for auditory effects. A nonauditory limit was proposed that is a parallel curve with peak pressures increased by about a factor of 2. For combat casualty purposes, a lethality criteria was developed by Bowen empirically based on animal data. A "threshold" injury curve was proposed that is a parallel curve with peak pressures reduced by a constant factor. Subsequent data analysis has shown that injury occurs at peak pressures less than these "threshold" estimates.

To provide a better criterion, Dodd, et al., (1990) proposed a peak pressure-duration curve to define conditions that would not produce "unacceptable" injury (any injury to the lung or GI tract or more serious injury to the upper respiratory tract (URT)). Separate curves were developed for multiple exposures. These relations have been used by MRMC as an interim criterion for making health hazards assessment of free-field weapon exposures.

All of the relations based on peak pressure and duration become unreliable in enclosures because reverberations make the duration so long that extreme injuries are always predicted. Attempts to find "equivalent" free-field waveforms are scientifically unjustified and have produced equally unreliable results. Consequently, MRMC began to experiment with using Jaycor's "generic" models to assess complex wave exposures.

In addition, the complex nature of blast waves in enclosures produces pressure traces that differ significantly from one location to another (because of the additions and cancellations caused by the myriad of wall reflections). The traces at a particular loca-

tion also differ significantly depending on whether an animal is present or not (because of the shielding and amplifying effects of the body). These variations are further confounded by the shot-to-shot variations seen in repeated tests.

Open Issues

Despite the considerable number of animal tests that have been conducted and the progress made in understanding the origin and mechanisms of damage, there are still questions that must be answered in order to obtain a satisfying and reliable assessment of hazard. First, in order to focus research effort, it is necessary to determine which organs are most susceptible, how severity increases with blast strength, and what aspects of blast correlate with these injuries. Second, since each new weapon produces a seemingly different blast signature, it is necessary to find a unifying approach that will anticipate and interpret new environments. Third, in order to determine the limits of biomechanical modeling to predict injury, a full validation of a single model must be made against all of the observed data. Finally, in order for the research to impact occupational exposure standards, a methodology is needed for making health hazards assessment that provides estimate of population effects and provides an estimate of error.

Objectives of Work

To address these issues, four objectives were set for the work. The first is to organize all of the animal data that has been collected at the Blast Overpressure Test Site in a form that can be used to determine the susceptibility of all organ systems to blast overpressure. The second is to evaluate computational fluid dynamics (CFD) as a unified approach to predicting and interpreting blast in complex geometries. The third is to develop and validate a biomechanically based, predictive model of gross lung injury that can be applied in all blast environments. The final objective is to develop a methodology for assessing hazard that provides an estimate of risk to the population, including estimates of confidence based on the statistical uncertainties of the animal data and of pressure measurements.

Technical Approach

The research is divided into five specific areas. The biomechanical response of the upper body are addressed in Area 1 (Thorax), Area 2 (Abdomen), and Area 3 (Head and Neck). The synthesis of this research into criteria for making health hazard assessment of blast overpressure exposure is addressed in Area 4 and the software for analyzing the physical environment and standardizing the assessments are addressed in Area 5. The evaluation and application of criteria for auditory hazard are addressed in Area 6.

In addition to these blast overpressure hazard issues, the contract has undertaken two special projects concerned with related hazard. The first project is to adapt our knowledge of injury from blast to estimating injury from kinetic energy projectiles used in current nonlethal weapons. The second project is to assess the broad medical, ethical, policy, legal, and operational considerations that must be addressed by nonlethal weapons, in general.

The following sections describe the objectives set and results achieved in each of these areas.

Area 1. Thoracic Response

The overall, gross pathology caused by blast exposure has been correlated with the work done on the lung as estimated by a simple model of the chest wall dynamics. This model does not take into account the physiological variation of the thorax and, therefore, cannot account for orientation effects or localized impacts. Furthermore, the single work value cannot be used to understand injury distribution within the lung or the loading delivered to other internal organs, especially the heart.

The thrust of this research area is (1) to extend the biomechanical model of the thorax and (2) to extend the correlate of injury. The goal is to be able to estimate injury due to localized impacts to estimate the internal localization of injury.

Task 1.1 Image-based Finite Element Model (FEM). The FEM of the thorax, previously developed from Visual Man images, has been extended to contain a representation of the diaphragm and the abdominal contents. The model has been used to compute the work done to the lung by external blast loading and compare these values with the pleural surface model and with the thoracic response model of Lobdell. The work correlate (which correlates with gross pathology) has been extended to the local maximum parenchymal compression, proposed by Fung, et al., (1986) as a mediator of lung tissue injury and for which a correlation with lung hemorrhage has been proposed by Liu et al., (1996). Qualitative agreement with the observed distribution of lung injury in sheep has been obtained.

The model provides a basis for the study of localized trauma, due to kinetic energy weapons or airbags, and for the localization of injury within the thoracic cavity.

"A Finite Element Model for Analysis of Thoracic Injury." Paul J. Masiello. Jaycor Technical Report J97-2997-01/024.

Task 1.2 Simplified Thoracic Response Model. Models of the chest wall forces from the Lobdell model have been added to the pleural surface dynamics model, which is used to compute the normalized work correlate, so that it can be applied to a wider range of impact conditions. A model of the skin had to be added so that blast loading and direct impact can be simulated by the same parameters. The thoracic response under impactor loading, originally used to validate the Lobdell model, have been reproduced in the extended model. The blast conditions have been recalculated and normalized work continues to be an excellent correlate of injury.

Task 1.3 Cadaveric Response Data to Thoracic Impact. The National Highway Traffic Safety Administration (NHTSA) has collected a considerable amount of data on the response of cadaveric thorax to impact loading. These data will be an invaluable resource in calibrating dynamic models and developing an understanding of injury mechanisms. Most of the data, however, has never been systematically reviewed because its current format does not allow ready access to the instrument output, photographs, movies, and test reports.

One recent test series, conducted by the University of Virginia, was selected to be put into a format that could be examined with Jaycor's Integrated Information System Software (IISYS). Movies were converted to digital format and synchronized with recorded data from accelerometers, force gauges, and pressure gauges. Applications were written that allowed side-by-side viewing of movies running in synchronization so that differences between cadaveric and dummy responses could be observed. The data was placed on CD-ROM and delivered to NHTSA for further evaluation.

"Out-of-Position Occupant (OOPS) ISO-1 and ISO-2 Series Tests." IISYS Session prepared for National Highway Traffic Safety Administration. March 1997.

Area 2. Abdominal Response

Previous animal studies have clearly demonstrated that injury to the abdominal organs, especially those containing air, has nearly the same threshold of occurrence under blast exposure as any of the organs in the thoracic cavity. Some studies indicate that the gastrointestinal tract may be the most sensitive organ system under repeated blast expo-

sure. Injury patterns in vehicular crashes, following the wide spread use of belt and air bag restraints, are beginning to show similar trends.

The thrust of this research area is (1) to develop a biomechanical understanding of the processes that connect external loading to internal injury within the abdominal cavity, (2) to develop correlates of injury based on the blast over pressure pathology database, and (3) translate this understanding into predictive models that can be incorporated into the INJURY software system.

No resources have been assigned to this research area.

Area 3. Head and Neck Response

Impact trauma to the head can produce devastating and costly injury to the skull, brain, and neck. This trauma can arise in vehicular accidents, projectile impacts, as well as many other situations. While there has been much experimental research and empirical data analysis to establish injury criteria, there does not exist a comprehensive understanding of the biomechanical processes that lead to injury. With this understanding many of the ambiguities of the current safety criteria can be eliminated and diagnosis and treatment procedures can be assisted.

The thrust of this research area is (1) to analyze previously collected data to determine trends and identify gaps, (2) to develop biomechanical models that accurately reflect the human physiology and dynamics, (3) to use those models to develop physically correct criteria for injury, and (4) to translate these findings into instrumentation and methodologies that can assess hazard.

Task 3.1 Hodgson Data Analysis. The most commonly used criteria for predicting head injury is the Head Injury Criterion (HIC), based on the center-of-mass acceleration of the head during impact. There is considerable controversy over the validity of the HIC. The most extensive attempt to validate the correlation was the cadaver studies of Hodgson from the early 1970s. Unfortunately, there are inconsistencies in the acceleration data which prevents a clear-cut confirmation.

A series of tests using a head surrogate has been conducted which reproduces the kinematic conditions of Hodgson's experiments. The tests were instrumented to provide, force, acceleration, and impact area data during the impact. The acceleration data was used to generate more reliable HIC values and the correlation with fracture estimated with logistic regression. The results show that measuring additional dynamic parameters of the impact can significantly improve the correlation with fracture.

A new physical model of the head was constructed, consisting of a solid aluminum hemisphere covered with a layer of neoprene rubber to simulate the scalp. The test series was repeated to give response data for a truly non-deformable skull model. Some vibration artifacts in the original tests were eliminated. The findings followed the pattern found earlier. A presentation of the findings was made to the National Transportation Biomechanics Research Center. Based on comments received at that presentation, the findings were compared to other statistical analyses of skull fracture by the automobile industry. A journal article has been prepared which is undergoing review at Department of Transportation (DOT).

"Analysis of Skull Fracture Data." Vander Vorst, M.J., Yu, J.H.Y., and Stuhmiller, J.H. Presentation to National Transportation Biomechanics Research Center, January 1997.

"Improvement of the Head Injury Criteria." Vander Vorst, M.J., Yu, J.H.Y., Stuhmiller, J.H. Jaycor Technical Report, J97-2997-02/026. May 1997.

Task 3.2 Cavitation in the Cerebral Spinal Fluid (CSF) Layer. High accelerations to the skull have long been speculated to produce damage to the brain without fracture to the skull. The observation of such injury on the countercoup side has been attributed to the formation of cavitation bubbles that do damage when they collapse. Quantitative data on this effect has been limited and mathematical models that incorporate the phase change process in the calculation of the fluid motions have not been developed.

Building on previous Jaycor work, experiments using surrogate head models and computational fluid dynamic simulations using the two-fluid version of the Equation Independent Transient Analysis Computer Code (EITACC) computer program were carried out. The experimental results show clear evidence of the formation of cavitation on both the coupe and countercoup sides and an extremely violent collapse process. The computational study reproduced the salient features of the experimental data and provides an interpretation of the behavior as the result of a combination of acceleration and local structural motion. These findings provide the basis for a biomechanical understanding of one of the head injury mechanisms. The work is documented in two technical reports:

"A Fluid Dynamic Study of the Skull-Brain Interaction. Part 1: Experimental Study." J.H.Y. Yu, P.C. Chan, and J.H. Stuhmiller. Jaycor Technical Report J96-2997-01/032. December 1996.

"A Fluid Dynamic Study of the Skull-Brain Interaction. Part 2: Computational Study." P.C. Chan, J.H.Y. Yu, and J.H. Stuhmiller. Jaycor Technical Report J96-2997-01/007. December 1996

Area 4. Health Hazards Assessment

The INJURY software package allows Walter Reed Army Institute of Research (WRAIR) to make standardized health hazard assessments from blast pressure traces measurements. In some cases, however, there are questions about nature of the blast field (spurious reflections, critical locations, etc.) raised by the pressure traces obtained. These questions cannot be resolved without a more complete understanding of the blast environment. In other cases, the interpretation of field instrumentation or the application of injury criteria arise.

The thrust of this research area is to provide specialized analyses in support of WRAIR's health hazard assessments to resolve these unusual issues.

Task 4.1 M120 Hazard Analysis. Test data taken around the 120-mm mortar being fired from an APC produced occasional pressure signals that exceeded the Z-line of Mil. Std. 1474C. In order to gain an understanding of this phenomena and to directly confirm with animal exposures the hazard of these conditions, a simulation is being constructed at the Blast Over Pressure Test Site. It is important to determine what geometric features are responsible for the complex internal pressure waves that are observed in field tests so these features can be incorporated in the simulation.

Jaycor's EITACC CFD program was used to analyze the blast field around the muzzle of the mortar and the BWAVES program was used to analyze the wave reflection process within the vehicle. Comparison of the computation with field data suggested that the blast from the muzzle of the mortar is itself complex and accounts for much of the observed complexity. Subsequently, free field data from the mortar confirmed this behavior. By constructing a blast distribution for the tube venting process and an unknown second process, it was possible to reproduce the characteristics of the pressure waves observed within the vehicle. The details are contained in the following technical report:

"Analysis of M120 Pressure Traces." K. K. Kan. Jaycor Technical Report J96-2997-01/014. December 1996.

Task 4.2 Guide to Implementation of INJURY Model Equations. Several investigators, who do not have access to the INJURY software package, want to use the pleural surface dynamics model and normalized work injury correlation in their research. The description in the Journal of Biomechanics paper is not sufficiently detailed for this purpose. To provide sufficient detail and sample problems that can be used to check the solutions, the following technical note was prepared:

"Sample Problems Using the INJURY Model." K.H. Ho and J.H. Stuhmiller. Jaycor Technical Note J96-2997-01/027. December 1996.

Task 4.3 Calibration of Blast Test Device. The Army Test Command (ATC) has built a Blast Test Device (BTD) based on Jaycor's plans for use in future field tests in which blast over pressure data will be collected. As part of their shakedown evaluation, they compared the side BTD pressure output for a free field exposure with pressure traces obtained from isolated free field gauges and the front BTD gauge with a gauge mounted on a flat plate. The pressure traces showed systematic differences, which they brought to WRAIR for resolution.

We conducted Computational Fluid Dynamics simulations, using the EITACC program, of the same free field blast wave (1) passing around the BTD, (2) passing a free field gauge, and (3) reflecting from a flat wall. The simulations show that the complex wave pattern around the cylinder makes the side gauges different from the incident gauge and the front gauge different from the gauge on the wall in just the manner seen in the data. To document these findings and to provide guidance to other researchers using the BTD who might have similar questions, a technical note was prepared:

"Comparison of the Blast Test Device with Free Field Pressure Measurements." P.J. Masiello. Jaycor Technical Note J96-2997-01/033. December 1996.

Task 4.4 Estimate of Lung Injury from Kinetic Projectiles. In order to get an estimate of potential lung injury due to kinetic energy weapons, a procedure was developed that used the Sturdivan correlation to translate the kinetic energy of the projectile into a probability of lethality, used the Jaycor correlations to estimate the normalized work that would produce this lethality, and used the Jaycor correlations again to estimate lung injury from the normalized work. This circuitous procedure is the best use of existing data until a biomechanical understanding (Special Project 1) is available. The methodology and results for a particular projectile is found in:

"Estimates of Probability of Lung Injury for MA/RA-83 and MA/RA-88." K.K. Kan. Jaycor Technical Note J96-2997-01/013. June 1996.

Task 4.5. Model Review by American Institute of Biological Sciences (AIBS). On November 5, 1997, Jaycor presented a comprehensive review of the blast injury modeling effort to a panel of the AIBS. This review also included presentations by the staff of the Department of Respiratory Research and a representative from Army Center for Health Promotion and Preventative Medicine (CHPPM). The review covered over 15 years of research that has led to the current generation of INJURY software for estimating blast overpressure hazard. The review addressed laboratory experiments, data analysis, and mathematical model development conducted under this effort, with an emphasis on the development of a lung injury model. The review also identified future Army needs and plans to meet those needs. The review is summarized in the following documents:

"Development of a BOP Health Hazard Assessment--Historical Summary."
J.H. Stuhmiller. Presentation to the AIBS Panel on BOP modeling. November 1997.

"Plans to Meet Modeling Needs." Presentation to the AIBS Panel on BOP modeling. J.H. Stuhmiller. November 1997.

Area 5. Software

One of the principal results of this research project into the mechanisms of injury is to produce software products that allow the findings to be used in a correct and consistent manner by the widest possible group of users. By capturing the methodologies in software that is distributed in executable form, MRMC can control the use and interpretation of the results.

The thrust of this research area is to continually develop, improve, and support those software products.

Task 5.1 PATHOS. A new version of PATHOS was produced that incorporates database changes suggested by WRAIR and that automatically updates previous versions of the pathology database. PATHOS 2.00 was delivered to WRAIR for further testing.

A slight revision, version 2.11, was prepared correcting some minor screen changes and allowing for automatic updating of previous database files that had been manually changed. The versions were shipped to WRAIR for evaluation.

Task 5.2 Data Archiving. Over the past ten years, Jaycor has archived virtually all of the blast and pathology data from tests at the Blast Overpressure Test Site in Albuquerque. The data had been converted to electronic format, however, those formats are not all the same (for example, the earliest pathology records were stored in an Informix database which requires special software to retrieve). Furthermore, the data was physically stored on magnetic media (floppy disks, Bernoulli drives, etc.) that are massive and of uncertain long-term reliability.

In this task, all of the data was converted to maintainable formats (Informix converted to MS ACCESS) and stored on CD-ROM. Six CD-ROM were produced: 3 of pressure traces, 2 of photographs, and 1 new version for use with IISYS. A listing of the electronic images that have been archived is contained in:

"A Compendium of Blast Pathology Photos in Electronic Format." K.H. Ho. Jaycor Technical Report J96-2997-01/015. June 1996.

Area 6. Auditory Model

The development of biomechanical models of the thoracic dynamics and the correlation of normalized work with gross pathology has provided a rational basis for setting non-auditory limits to blast loading that eliminates the previous uncertainty in the Mil. Std. 1474C Z-line. Human volunteer studies at the Blast Over Pressure Test Site indicate that the auditory limits of the Mil. Std. may also be overly conservative and therefore inappropriately restricting weapon training.

The thrust of this research area is (1) to collect, organize, and analyze existing auditory exposure data to determine the validity of the Mil. Std., (2) to evaluate other standards and models to determine if discrepancies can be eliminated and improve them as required, and (3) incorporate the final auditory hazard methodology into INJURY.

Task 6.1 Review of Existing Models. A literature review of auditory models, data, and injury criteria was conducted. The criteria have been organized into a common format that can be cross-compared. Existing simulation models have been reviewed. In addition, the HEL dynamic model was obtained and run to demonstrate that it could reproduce the test cases. The findings are contained in:

"Evaluation of Current Auditory Models." P.C. Chan. Jaycor Technical Report J96-2997-01/012. July 1996.

Using attenuation spectra developed for hearing protection devices, pressure time histories at the eardrum were estimated from free field data. The HEL model could then use that pressure data. A series of human volunteer tests were simulated, where auditory data was collected. The injury predicting output of the model was compared with the observed hearing decrements (pass/fail basis). The model proved to have little ability to discriminate between safe and unsafe conditions. At a North Atlantic Treaty Organization (NATO) auditory specialist meeting, Dr. Price of HEL, co-developer of the model, revealed that the model we had been given was for the cat. The results of this analysis are found in the presentation

"Addition of an Auditory Model to INJURY." Presented to the NATO Auditory Specialist Meeting, Aberdeen MD. July 10, 1996.

Task 6.2 Organize/Analyze Existing Data. Dr. James Patterson, consulting to Jaycor, is working with the staff at USAARL to qualify and transfer human study auditory data into a format that can be used for analysis. A preliminary report has been issued that contains a small number of data:

"Pressure Measured Under Earmuffs Worn by Human Volunteers During Exposures to Blast Overpressures." B.T. Mozo and J.H. Patterson. US Army Aeromedical Research Laboratory Technical Memorandum TM-96-39. September 1996.

The data (4 CD's) from US Army Aeromedical Research Laboratory (USAARL) and EG&G for the Blast Overpressure Studies (BOP) have been archived. Dr. James Patterson has provided assistance in obtaining missing data, clarifying data field names, and verifying pressure traces. A reference set of free field and under-muff pressure traces has been collected for the mortar tests at all 3 distances and each of 7 intensity levels. The free-field pressure data set is also applicable to the non-linear plug tests using the mortar, but no under-plug pressures were taken. For the bunker tests, under-muff pressures have been received, but the external pressures taken from the calibration tests are still being documented by EG&G. The temporary threshold shift (TTS) data are contained in audiometric databases that also include the baseline thresholds for all subjects.

Task 6.3 Evaluate Existing Criteria. Representative data from the USAARL and EG&G studies have been analyzed in terms of the current auditory injury criteria. A preliminary evaluation considered representative data from each exposure condition. For each exposure condition, injury rate was found to increase systematically with the intensity of exposure as measured by the explosive weight, peak pressure, A-weighted energy, or P-weighted energy. These correlations were statistically significant ($p < 0.05$). The Army Research Laboratory (ARL) model showed no significant correlation when the under muff data was used as free field input. The findings are documented in:

"Evaluation of Impulse Noise Criteria Using Human Volunteer Data." P.C. Chan, K.H. Ho, and J.H. Stuhmiller. Presentation dated June 24, 1997.

The pressure data collected under the earmuffs were used to evaluate the unprotected injury criteria. This comparison assumes that the free field pressures are the same as that in the ear canal. Injury was not observed until 175 dB, more than 30 dB above the level set by the military standard. For volunteers wearing the modified muffs, injury was not seen until 190 dB, independent of duration and number of repetitions. The military standard and Pfander's criterion set lower thresholds, while Smoorenburg is higher at few repetitions and lower at 50 and 100 repetitions. The findings are documented in:

"Auditory Injury Criteria Evaluation." P.C. Chan, K.H. Ho, and J.H. Stuhmiller. Presentation dated August 13, 1997.

Task 6.4 SUNY Data Organization and Analysis. This task will organize, qualify, and archive the animal data on impulse noise hazard collected under previous MRMC

contracts at the State University of New York (SUNY). Existing data will be entered into a relational database defining test conditions, noise exposure measures, and pathological outcomes. The pressure-time history data will be transformed into a compact binary format and stored. Drs. Hammernik and Patterson, who were involved in the original experiments, will also analyze the data to determine the acoustic measure that provides the best correlation with injury. Jaycor will transform the data into an IISYS session for easy access.

A kick-off meeting was held at SUNY to define schedule and the database structure. A preliminary structure was discussed and will be used to collect the data. The data transfer phase is expected to last a few months. Jaycor will review sample data as it is generated.

Task 6.5 MAAWS Hazard Assessment Support. The Multi-role Anti-armor Anti-personnel Weapon System (MAAWS) has received conflicting auditory hazard assessments in the past, one assessment recommended restricted training, while a second recommended no exposure. The assessments were both based, in part, on results of the human volunteer testing at the Blast Test Site.

Jaycor has analyzed the free field exposure data and has evaluated the ability of existing acoustic parameters to correlate with the injury observations. In particular, a logistic regression to the Military Standard noise level was generated that suggests that protection of 95% of the population would be achieved at levels below 189.4 dB (50% confidence) and below 188.5 dB (95% confidence). These levels are considerably higher than the previous USAARL estimates, primarily because the Jaycor analysis uses all of the data in assessing the threshold, while the USAARL estimates use only small test samples. These differences were revealed in technical interchange meetings. Unfortunately, no unified position could be taken with the current analysis status. The results are summarized in:

"Auditory Injury Criteria Evaluation." K.K. Kan, P.C. Chan, K.H. Ho, and J.H. Stuhmiller. Presentation to WRAIR. December 1, 1997.

Effort has been focussed on organizing and qualifying the EG&G data and in developing, first a clear identification and later a consensus for statistical interpretation of the data.

Special Project 1. HHA for Projectile Impact

There is a growing need to make health hazard assessments (HHA) for nonlethal weapons that deliver a direct impact to the body. There is very little animal test data for these situations and conducting case-by-case animal tests for all of the weapons and deployment combinations would be prohibitively expensive.

This task area will combine the biomechanical models and injury correlates developed for blast with instrumentation to characterize impact loading to produce a methodology for making hazard assessments for projectile impacts.

Six sub-tasks are envisioned in this area.

Review literature to identify data and injury correlates.

Extend thoracic response model to projectile impact.

Develop simplified response model for rapid analysis.

Develop a test apparatus for characterizing projectile impact.

Develop a field test unit employing a large target area.

Develop software to standardize the hazard analysis.

Task SP 1.2 Extend Thoracic Response Model to Projectile Impact. The finite element model developed for investigating distributed thoracic injury was used to determine response under impact loading. The validation was extended to include oblique impact tests conducted by the automobile industry. A series of simulations was made to determine thoracic response and, in particular, the generation of work in the lung parenchyma, by projectiles of increasing cross-sectional area. In addition, the response of the thorax to pressure loading, both localized and whole body, was found. These results form a basis from which the simplified spring-mass-damper models can be calibrated to give an accurate response over a wide range of trauma. These additional findings were incorporated in the previous report as the revision:

"A Finite Element Model for Analysis of Thoracic Injury." Paul J. Masiello. Jaycor Technical Report J97-2997-01/024 Revision 1.

Task SP 1.3 Develop Simplified Response Model for Rapid Analysis. The INJURY programs for blast injury assessment use a model for chest wall response that takes into account the inertia of the chest wall and the pressure developed in the lung due to the rapid compression. In short duration blast exposures the chest wall deflections are sufficiently small that the thoracic stiffness can be ignored. As part of the thoracic modeling effort, the model is being extended to include these effects. A simplified model is needed by the non-lethal weapons (NLW) assessment program to make rapid analyses.

The spring-mass-damper models used in the automotive industry to predict chest wall motion are designed strictly for local impact, while the INJURY model is concerned with the gross motion of the chest. We need a single model that can describe both, so we can calibrate the response to injury data collected for blast and apply it to NLW impacts.

The results of the finite element model of the thorax have been used for this purpose. The effective area of the sternum mass has been determined by comparing the chest wall response between models. The simplified model has been used to compute the normalized work for all cases in the blast pathology database and then used to evaluate lung contusion arising from the NLW impacts. The model is described in:

"A Model for Lung Injury due to Air Blast and Blunt Impact." Kevin H.H. Ho, Kit K. Kan, James H. Stuhmiller. Jaycor Technical Report J96-2997-05/060. August 1997.

Task SP 1.4 Test Apparatus for Characterizing Projectile Impact. The body's response to projectile impact depends on the spatial and temporal loading time history. This task will develop a laboratory test apparatus that can determine the loading parameters.

A multiple load cell device was designed and built to collect preliminary data. Those results showed that the loading duration was less than 1 ms and, therefore, would be too rapid for the TekScan load distribution sensor to capture. The design concept then shifted to using a covering material that will leave a clear indication of the impact area. Several candidates were screened and a kind of neoprene rubber was judged most durable. The multiple load cell design was found to have only a limited impact area where reliable force data could be collected. The design was refined with a unidirectional piston arrangement that gave accurate loading data for all impact points on a 5 inch diameter target plate. The results for the "bean bag" projectile show that the loading characteristics vary depending on the orientation of the bag when it hits the target. Results are documented in:

"A Laboratory Device for the Measurement of Load and Impact Area of Nonlethal Weapons." James H-Y Yu. Jaycor Technical Report J96-2997-05/022. October 1996.

Task SP 1.5 Develop a Field Test Unit Employing a Large Target Area. The scatter of the nonlethal projectiles is so great that the requirements for the load measuring device were altered to have a target area of 13" x 18". This larger area required that the design be totally rethought. A new design was developed that employs multiple force transducers supporting a larger target plate. A prototype was developed and tested. Effects of the covering material were discovered and a standard surface condition was selected.

A presentation of the progress in developing the field unit was given to John Cline of Armament Research, Development and Engineering Center (ARDEC). The larger force device was able to record impacts over its entire area, but the natural vibration of the plate introduces temporal variations that compete with the impact itself. Various concepts to

dampen the vibrations were presented, but those that were successful in reducing the plate vibration reduced the impact force.

A field test of the large format force device was made at Aberdeen Proving Grounds, MD in March 1997. A variety of NLW projectiles were employed. The instrument functioned without problem and the traces were taken back to Jaycor for further analysis. Estimates of the impulse and duration of impact have been made. The data will be used to make Health Hazard Assessments. The description of the field test unit, a summary of results from the APG tests, and a description of the calibration methods are found in:

"A Field Test Device for Measuring KE-NLW Impact Loads." James H. Yu. Jaycor Technical Report J96-2997-05/045. August 1997.

Based on the discussions, it was decided to undertake an investigation of mathematical analysis techniques to separate the natural vibration models from the projectile impact. A mathematical technique is being developed to use the measured support forces to construct a modal representation of the plate motion and then extract the true, external impact force. Results for single projectile impacts have been encouraging. The description of the technique is found in:

"Characterization of Impact Force." Kit K. Kan and James H. Stuhmiller. Jaycor Technical Report J96-2997-05/046. August 1997.

A second large area, field test unit was constructed and sent to ARDEC for evaluation.

Task SP 1.6 Clay Impact Tests. The previous analysis has shown that thoracic response depends on both impulse and duration and that the local deformation of the body surface or clothing can significantly affect these values. Penetration and local contusion could also have the same dependencies. Exploratory tests are conducted to determine what the effects of skin and clothing may have on the loading and to determine the relation of loading to indentations in clay.

A nail gun was used to produce a loading time and spatial distribution similar to a nonlethal weapon. Layers of rubber simulating skin and muscle and layers of cloth representing clothing were interposed. Generally the impulses were lowered and the duration lengthened. Clay backing produced even greater reduction and spreading of the force. A relation between the indentation in clay and the force parameters was not evident. The results are summarized in:

"Nail Gun Impact Test Device." J.H.Y. Yu. Presentation to ARDEC. December 9, 1997.

Task SP 1.7. Software for Estimating Blunt Trauma Effects. A collection of hazards from nonlethal weapon impact has been identified, including lung contusion from gross chest wall motion, local penetration, and lethality. Correlation of each of these hazards has been put in a software package, whose input is the kinematics of the projectile and whose output is a table of probabilities of each outcome. This analysis provides a standardization of the interim hazard assessment process.

Task SP 1.8 Presentation of Project Results. On December 9, 1997 a presentation was made to ARDEC technical staff reviewing all of the results of this special project. The review was documented in a series of presentations:

"Health Hazard Assessment for Kinetic Energy Non-Lethal Weapons--Summary." J.H. Stuhmiller. December 9, 1997.

"Laboratory Test Device for Kinetic Energy Non-Lethal Weapon Impact Loads." J.H.Y Yu and J.H. Stuhmiller. December 9, 1997.

"Field Test Device for Kinetic Energy Non-Lethal Weapon Impact Loads." J.H.Y Yu and J.H. Stuhmiller. December 9, 1997.

"Health Hazard Assessment Methodology." K.K. Kan, K.H. Ho, and J.H. Stuhmiller. December 9, 1997.

Special Project 2. NLW Biological Effects Broad Issues Study

Considerable interest has developed within the military services to have nonlethal options to deal with various situations that develop in peacekeeping operations. Many technologies (chemical agents, kinetic projectiles, microwave and rfr waves, etc.) are being considered, but there is great uncertainty about what criteria should be applied to weapons that are supposed to "temporarily incapacitate," but not permanently "harm" the targets. The identification of these concerns has importance to biological research and to the development of medical treatment strategies.

The thrust of this special project is (1) conduct interviews with individuals and organizations representing medical, legal, policy, operational, ethical, and other perspectives, (2) summarize the state of knowledge of biological effects from microwaves and rfr, and (3) summarizes the findings from the perspective of research directions.

The purpose of the study is to identify the biomedical issues that the Department of Defense must resolve in order to develop, acquire, and field non-lethal weapons. The scope of the study is to interview a variety of organizations, inside and outside of the military, to understand the concerns that must be addressed and to summarize the scientific literature to understand the data that will be required to answer these questions.

Interviews were conducted with a wide range of organizations so that a broad perspective could be achieved. A partial list of those organizations included:

- Air Force Medical Operations Agency (AFMOA)
- Army Medical Research and Materiel Command (MRMC)
- Army Center for Health Promotion and Preventative Medicine (CHPPM)
- OASD, Special Operations and Low Intensity Conflict
- Office of Protection from Research Risks, NIH
- Office of Munitions/Strategic and Tactical Systems
- Nonlethal Coordination Cell, Joint NLW Directorate
- Federal Bureau of Prisons, Department of Justice
- Dismounted Battlespace Battle Laboratory
- Directorate of Combat Developments, US Army Infantry Center
- US Central Command
- US Special Operations Command

The interview process included a briefing on NLW technologies and a checklist of questions of interest. Responses varied, but there was general interest in the subject and strong feelings about what actions should be taken. The comments were compiled into a complete narrative and were sorted into categories. Eight principal areas of concern were identified that touch upon biological research. They are:

- Overlap of incapacitating and harmful acute effects
- Operational effectiveness
- Countermeasures and protection
- Care and treatment
- Long term effects
- Operator safety
- Credibility of data
- Human exposures

The findings were presented to the AF Surgeon General's office at Bolling AFB and to the Human System Center at Brooks AFB. A case study was prepared describing the events leading to the abandoning of the Army's Laser Countermeasures System (LCMS). The technical reports generated by this effort include:

"NLT Bioeffects Broad Issue Study. Volume 1: Technical." Stuhmiller, J.H. Jaycor Technical Report J97-2997-04/039. March 1997.

NLT Bioeffects Broad Issue Study. Volume 2: Appendices." Stuhmiller, J.H. Jaycor Technical Report J97-2997-04/039. March 1997.

"The Laser Countermeasure System (LCMS): Case Study of a Nonlethal Weapon System Acquisition Program." Jaycor Technical Report J96-2997-06/001. December 1996.

A related report, covering work done under a previous phase of the Jaycor biomechanics program, but only recently completed deals with the mission-relation issues of nonlethal weapons. The findings are found in:

"Mission Applications of Non-Lethal Weapons." Hannigan, T.J., Raff, L., and Paschall, R. Jaycor Technical Report J96-2997-06/002. August 1996.

Summary of Results

An anatomically based finite element model of the human thorax has been developed. The total energy delivered to the compression wave in the lung under blast loading is found to be quantitatively similar in the detailed FE model and the simplified INJURY model. The detailed model, however, provides insight into the distribution of injury within the lung, a critical link to understanding lung function changes, and provides a means for estimating lung contusion from kinetic projectile impacts. Cooperative research with the Department of Transportation provides access to human cadaver data that will validate the model.

The dynamics of the head under direct impact has been modeled with anatomically based finite element models. Data from previous cadaver testing has been collected and assessed, leading to new physical tests to clarify previous data anomalies. The result is a statistically significant improvement in the criteria for head injury and the start of placing both skull fracture and brain injury on a biomechanical basis.

The INJURY software has now undergone successful independent validation. The software has been delivered to other Department of Defense activities along with implementation guidelines and test problems. The implementation of the blast test device as a standard test instrument is proceeding and guidance has been developed for field calibration and evaluation. Several weapon systems have been evaluated.

Data of previous human and animal exposures to impulse noise is being collected so that the validity of the current auditory standard can be determined. Preliminary analysis of the human volunteer data from the Blast Test Site indicates that the Military Standard is overly conservative. Data originally collected at SUNY will be used to assess the safety margin between temporary and permanent auditory injury. These analyses have assisted the assessment of the MAAWS.

The remainder of the contract effort will be directed toward finalizing and documenting the blast overpressure hazard assessment. The work includes entering the last of the BOP animal data and the auditory data into the blast pathology database; evaluating existing auditory models and criteria; finalize the INJURY and PATHOS software; compute the injury correlation based on the complete data set; and prepare the final report for the contract.

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